

## **Fractionation of Infiltration and Inflow (I/I) components in urban sewer systems with regression analysis**

Détermination de l'origine de l'infiltration et des apports dans un système d'assainissement urbain par une analyse de régressions

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### **RESUME**

La gestion des systèmes d'assainissement nécessite des données sur la variabilité et le volume des sources d'eau usée dans les réseaux urbains. En particulier, ce sont l'infiltration de l'eau souterraine et l'entrée de l'eau superficielle (I/I) qui sont importantes pour la décision de réhabilitation et d'opération du réseau d'assainissement. Dans cette communication, une méthode est présentée qui soutient l'identification et la quantification des apports I/I. La méthode est fondée sur une combinaison des approches de modélisation qui représentent les fractions du débit différentes dans le réseau d'assainissement. Les paramètres du modèle sont dérivés par une application de la régression linéaire multiple. La méthode a été appliquée pour la ville Dresde. Les résultats de la méthode de fraction sont présentés et discutés.

### **ABSTRACT**

The management of urban sewer systems requires data about variability and discharge of typical waste water sources in urban catchments. Especially the infiltration of groundwater and the inflow of surface water (I/I) are important for decisions about rehabilitation and operation of sewer networks. In this paper a new methodology is presented which supports the identification and quantification of I/I components. The methodology is based on a combination of model approaches representing the different flow fractions in sewer networks. Parameters of the models are deduced by the application of a multiple linear regression. The methodology was applied for the City of Dresden. Results of the fractionation method are presented and discussed.

### **KEYWORDS**

Combined water fractionation , infiltration, inflow, I/I, multiple linear regression, wastewater components.

## 1 INTRODUCTION

Fractions of the total discharge in urban sewer systems are sewage of households and industry, rainwater, infiltrated groundwater, drainage water and eventually the inflow of surface water courses (e.g. overflows of springs or creeks). The discharges of domestic and non-domestic wastewater as well as the discharge of rainwater determine the hydraulic and procedural design of the sewer network and the wastewater treatment plant (WWTP). But also infiltration of groundwater and inflow of drainage and surface water sources - also referred to as infiltration/inflow (I/I) - represent a basic component which influences significantly costs and operation. I/I induce an increase of the hydraulic load and mostly a lowering of the waste water treatment efficiency and thus additional costs and a deterioration of the receiving water (ELLIS, 2001). Furthermore, I/I can cause a broadening of floods in urban areas and the endangerment of urban infrastructure during flood events. Otherwise, I/I have some positive impacts on the operational process of sewer networks and the urban infrastructure. The increased total discharge due to I/I causes advanced flushing, lower concentrations, and maybe a significant decrease of sewage temperature and increase of nitrate in the systems. The consequences are reduced anaerobic processes and the decrease of sedimentation processes, smell development and corrosion in sewer pipes. Furthermore, the drainage of groundwater could prevent the groundwater table from rising and wetting urban areas (GUSTAFFSON, 2000), e.g. in former mining areas.

For the assessment of operation strategies, for the future development of the systems and for the design of sewage constructions it is necessary to analyse the flow fractions in sewer systems. Balance methods to assess flow components are usually applied (DE BENEDITTIS and BERTRAND-KRAJEWSKI, 2004). These methods which require measurements of sewage flow, wastewater discharge and rain intensities, afford the fractionation of rainwater inflow and I/I. Disadvantageously, balance methods can not differentiate between the sources of I/I, i.e. groundwater, drainage water, surface water. In order to get more detailed information about I/I sources, methods based on chemical characteristics of sewage water were developed such as isotope methods (KRACHT *et al.*, 2003) or tracer measurements (KRACHT and GUJER, 2004). However, these methods are costly and are applicable when certain boundary conditions are fulfilled only, such as a different oxygen isotope composition of drinking and groundwater. Beside measurements, I/I sources are assessed by modelling. The models are based on conceptual (BELHADJ, 1995; GUSTAFFSON *et al.*, 1999) and physical approaches (GUSTAFFSON *et al.*, 1997, RODRIGUEZ *et al.*, 2004). However, they have a high parameter uncertainty and extensive data requirements.

In the project presented here it was our aim to develop a method which allows the fractionation of I/I components based on reproducible mathematical methods and commonly available data. The method links model approaches for the different I/I components. It includes the identification of the I/I sources by hydrograph and correlation analyses, the description of the processes with physical-conceptual approaches and the calibration of basic parameters with multiple linear regressions. The developed methodology is applied and tested for the sewer system of the City of Dresden. The example shows data requirements and results of the methodology.

## 2 INVESTIGATED CATCHMENT AND DATA

The Dresden catchment covers an area of 98 km<sup>2</sup> with approximately 470,000 inhabitants. Industrial areas with significant contributions to the waste water discharge are situated within the city catchment, too. The sewer system consists of 900 km

combined sewers, 380 km foul water pipes and 340 km storm water pipes. The city is situated along the river Elbe. The average runoff of the river yields  $327 \text{ m}^3/\text{s}$ . During flood events the river water may enter the sewer system via flooded manholes and leaky CSO-gates which should cut off sewer and river system when the water level in the latter is higher. In the past, sewerage technology included the flushing of the sewer pipes by runoff from creeks or springs, which were connected to the system. Some of these surface water sources are still connected with the network. Parts of the sewer system are temporary or permanently influenced by the aquifer (KARPF and KREBS, 2004).

For the following investigations flow data of the WWTP, rain intensity, air temperature, groundwater levels, water levels of the river Elbe and flow measurements in a local creek were used. The data were available from 1995 to 1999 with a resolution of 1 day except for groundwater measurements which were measured every 8 days. Additional water supply data of the year 1999 were used for verification purposes.

### 3 IDENTIFICATION OF I/I COMPONENTS

The dry weather flow (DWF) in urban sewer systems, which can be deduced by the exclusion of rain water and snow melt runoff by statistical or by hydrological methods (WEISS et al., 2002; WITTENBERG and BROMBACH, 2002), is characterised by the variations of the different input sources. The daily and weekly and in some catchments also seasonal variations of the DWF depend mainly on the drinking water consumption and thus on the domestic and industrial waste water discharge. Seasonal and yearly variations are often induced by groundwater and surface water sources. Peak flows during dry weather could be induced by floods or rain derived infiltration (RDI) - also referred to as fast infiltration component which describes an increased inflow after rain events.

In order to investigate the dynamics of waste water discharge the Dresden data of DWF for the year 1999 were classified by months and week days (Figure 1, left). Thus, the influences of industry and tourism and other seasonal and weekly differences can be identified. It can be seen, that the weekly variation is small. There is no significant difference between working and weekend days. Furthermore, the monthly flow differs. The increased values from February to March apparently are induced by I/I sources. Drinking water supply data support the assumption, that seasonal variations are not induced by varying drinking water consumption and sewage discharge, respectively (Figure 1, right).

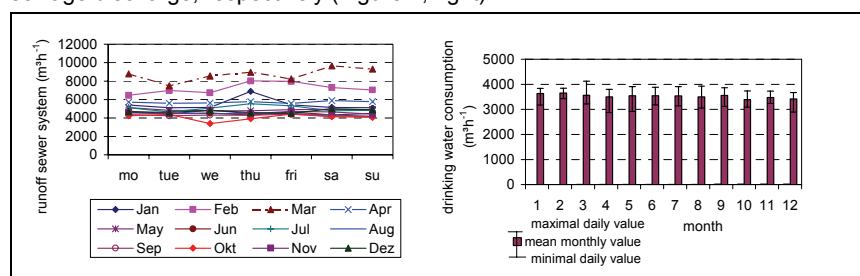


Figure 1: Total discharge in the sewer system of the city of Dresden classified by weekday and month (left) and drinking water supply (right) in 1999

The relationship between flow in the sewer systems and hydrological data is assessed by a correlation analysis. Figure 2 illustrates correlations between measured DWF, water level measurements of the river Elbe, runoff measurements of

a local creek, summarised rain heights of 7 days before the considered dry-weather day and the mean distance between groundwater level and sewer pipe inverts.

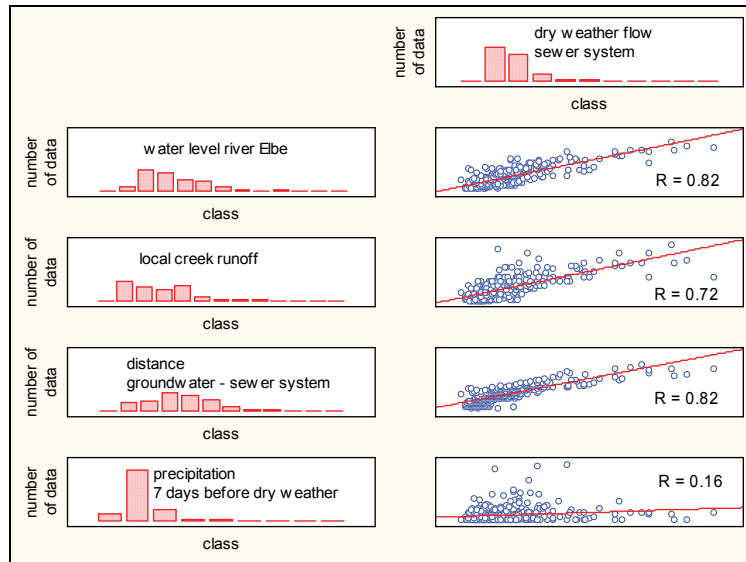


Figure 2: Distribution and correlation of DWF, water level in the river Elbe, runoff in a local creek, distance between groundwater and sewer system and summarized precipitation 7 days before dry weather

A strong correlation between the flow in the sewer system and the groundwater and local and regional surface water courses can be observed, whereas the river and groundwater shows a closer correlation with the sewage flow than the correlation between the local creek and sewage flow. The precipitation shows a low correlation with the DWF. It is concluded, that surface water courses and groundwater are much more important for the sewage flow during dry-weather periods than local rainfall before these dry weather periods. This conclusion can also be confirmed by the investigation of rain derived infiltration (RDI).

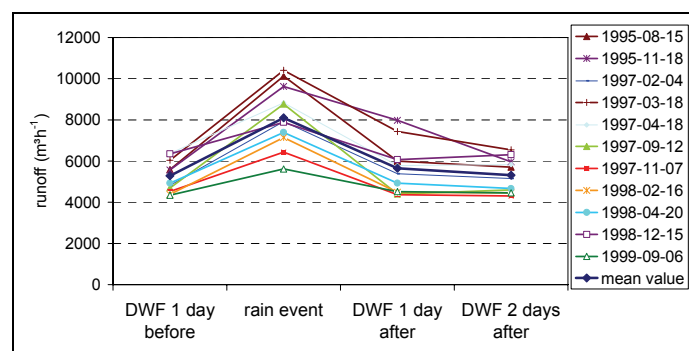


Figure 3: Flow in the sewer system of the City of Dresden before and after rain events

RDI was investigated by the comparison of flow rates before, during and after rain events. The result is illustrated in Figure 3. The DWF 2 days after the rain events have similar magnitudes as before rain events, i.e. an influence of the events is not longer detectable. This result, which can be observed in different seasons, is apparently independent of the climate conditions. It is concluded that RDI has a low importance in the considered catchment and that RDI can be neglected by using two dry days after the rain event for DWF-examinations.

## 4 METHODS

### 4.1 Approaches to model I/I components

According to the correlation and hydrograph analysis, groundwater and surface water sources were identified as main contributors to I/I in the catchment of the City of Dresden. The approaches applied for the various components are described in the following.

The approach for groundwater infiltration is based on the law of Darcy (equation 1). The factor  $k_{in}$  represents the permeability of the pipes in ( $\text{m}^3 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ). It is assumed, that the pipe reacts like an ideal drain. That means, the area  $A_{GW}$ , which is wetted by groundwater, is permeable. The hydraulic slope depends on the pressure height ( $\Delta h$ ), represented by the difference of groundwater level and pipe water level, and the mean distance ( $\Delta d$ ) between leakage area  $A_{GW}$  and groundwater level.

$$Q_{in} = k_{in} \cdot A_{GW} \cdot \frac{\Delta h}{\Delta d} \quad \text{equation 1}$$

Thus the upper limit of infiltration  $Q_{in}$  is  $k_{in} \cdot A_{GW}$ . For the assessment of permanent and temporary surface water inflows several approaches were used depending on data availability. The calculation of surface water inputs during flood events is described with equation 2 based on the approach of Toricelli. The inflow ( $Q_{flood}$ ) of surface water depends on the pressure height ( $\Delta h_{SW}$ ), the leaky area ( $A$ ) and a coefficient describing the shape of the openings ( $\mu$ ). In order to simplify equation 2 the parameters are combined to one factor ( $k_{flood}$ ).

$$Q_{flood} = \mu \cdot A \cdot \sqrt{2 \cdot g \cdot \Delta h_{SW}} = k_{flood} \cdot \sqrt{\Delta h_{SW}} \quad \text{equation 2}$$

Permanent inflows of surface water courses ( $Q_{inflow}$ ) are modelled by a simple conceptual approach (equation 3) consisting of a coefficient ( $k_{SW}$ ) and the runoff in a local creek ( $Q_{SW}$ ).

$$Q_{inflow} = k_{SW} \cdot Q_{SW} \quad \text{equation 3}$$

### 4.2 Multiple linear regression

The approaches of the I/I-components were combined in equation 4, by which the DWF for a certain time step (in our case: one day) is estimated.

$$Q_{DWF} = k_{GW} \cdot \sum_i \left( A_{GW,i} \cdot \frac{\Delta h_{L,i}}{d_{k,i}} \right) + k_{flood} \cdot \sum_j \left( \Delta h_{SW,j}^{0.5} \right) + k_{SW} \cdot Q_{SW} + Q_W$$

$\underbrace{\hspace{1.5cm}}$   
 dependent  
variable

$\underbrace{\hspace{1.5cm}}$   
 infiltration  
coefficient

$\underbrace{\hspace{1.5cm}}$   
 infiltration  
variable

$\underbrace{\hspace{1.5cm}}$   
 surface water  
coefficient 1

$\underbrace{\hspace{1.5cm}}$   
 surface water  
variable 1

$\underbrace{\hspace{1.5cm}}$   
 surface water  
coefficient 2

$\underbrace{\hspace{1.5cm}}$   
 surface water  
variable 2

$\underbrace{\hspace{1.5cm}}$   
 constant

i... index sewer pipe  
j...index sewer manhole/ CSO

equation 4

A multiple linear regression method was used to identify the coefficients  $k_{GW}$ ,  $k_{SW}$ ,  $k_{flood}$  (equations 1 - 3). The constant value of  $Q_w$ , also estimated with the regression, represents the waste water discharge. The DWF ( $Q_{DW}$ ) is the dependent variable. Inputs of the linear regression method are datasets of the dependent and independent variables. These sets stand for different process phenomena represented by the fluctuating water levels of aquifer and surface water and the reaction of the sewer system. The dependent and independent variables were provided by pre-processing.

### 4.3 Pre-processing

Except for the surface water variable 2 in equation 4, which is based on flow measurements in a certain small local creek, the linear regression requires data pre-processing.

The determination of DWF  $Q_{DW}$  is based on flow measurements of sewage flow at the waste water treatment plant inlet, rain intensity measurements in the catchment and additional measurements of the air temperature. Days of DWF are defined by a maximum rainfall intensity of  $0.3 \text{ mm} \cdot \text{d}^{-1}$  at the considered day and one day before in order to exclude RDI (see above). Furthermore, 3 days before and on the respective DWF-day the air temperature should not be in the range of  $-2^\circ\text{C}$  and  $+2^\circ\text{C}$ . By using this condition the runoff of snow melt water in the sewer system is excluded.

The calculation of the infiltration-based variable requires the estimation of the groundwater level near the sewer system elements and the waste water level in each pipe of the considered area. Hence, groundwater level measurements were spatiotemporally interpolated and linked to the sewer pipe location. Waste water levels in the sewer pipes were simulated with a hydrodynamic network model. Surface water variable 1 (equation 4), representing the temporary influence of the river Elbe, was identified by the linkage of river water levels and the levels of sewer network elements (manholes, CSO-gates, CSO-weirs) in a geographic information system.

## 5 RESULTS

The results of the multiple linear regression are summarised in Figure 4.

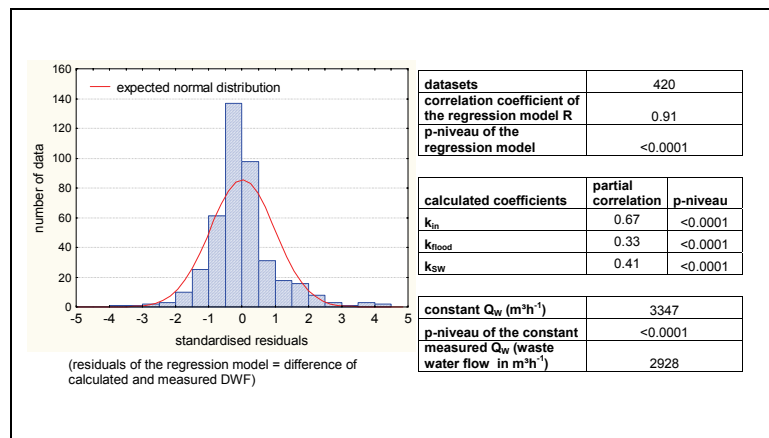


Figure 4: Assessment of the quality of the linear regression method and the deduced coefficients of the regression model for DWF estimation

The comparison of calculated values and the measured data of DWF shows a strong correlation ( $R = 0.91$ ). Furthermore, the regression model and the individual coefficients have a high significance ( $p < 0.0001$ ). The partial correlation coefficients give an idea about the relevance of I/I components. The residuals between calculated DWF and the measured DWF yield a good approximation of the normal distribution. The comparison of measured waste water discharge and the constant value support the assumption that the constant value can be interpreted as waste water discharge. It can be concluded, that the deduced model (equation 4) is applicable to predict the DWF and variations of single I/I components in the investigated catchment.

The modelled hydrographs of the I/I components between 1995 and 1999 are illustrated in Figure 5. A comparison with measured values shows, that seasonal fluctuations of the DWF are well described by the regression model (Figure 5, left). With an average value of 74 % of the I/I volume the infiltration component  $Q_{in}$  is the most important contributor to I/I (Figure 5, top right). Permanent surface water input yields about 23% and temporal inflows of surface water induced by flood represents 3% of the I/I volume. However, in a short-term run the surface water sources may dominate I/I. This is shown by the peak flow of a spring flood event in 1999, where more than 50% of the I/I-volume was induced by surface water courses (Figure 5, bottom right).

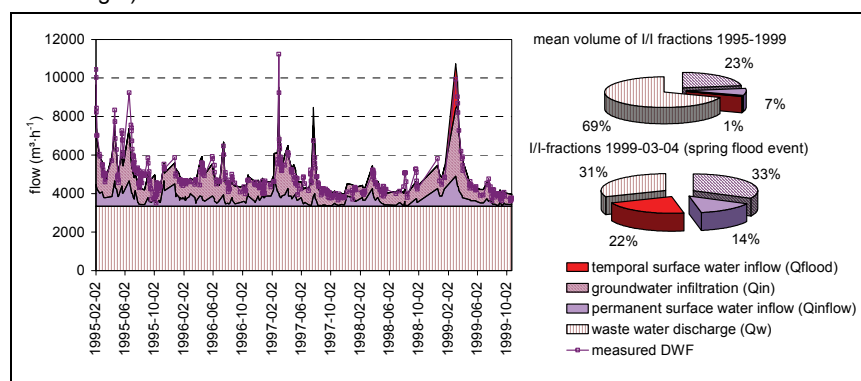


Figure 5: Dynamic fractionation of the DWF in the City of Dresden, long term and short term balance

## 6 CONCLUSIONS

The combination of model approaches to simulate I/I processes and the calibration of the parameters with multiple linear regression methods offer opportunities to quantify the various components of I/I. The approaches which are linked in a regression equation must be reduced to linear or quasi linear models. This is a disadvantage for a detailed process representation. On the other hand, such simplified physical and conceptual model approaches yield satisfying results regarding general statements about the components. An important requirement of the described methodology is the availability of groundwater and surface water data. Furthermore, flow data of the sewer network at least in the WWTP inflow, rain intensity in the catchment and temperature measurements are necessary to separate DWF from the total discharge.

The deduced regression model for the City of Dresden illustrates a high significance of estimated coefficients. These results underline the influence of numerous I/I-components on the variation of the DWF. With a fraction of 74 % of the total I/I volume groundwater infiltration is the most important contributor to I/I in the study.

The annual input volume of permanent and temporary surface water yields about 26 %. But, surface water fractions increase rapidly and may become dominant during flood events.

With the introduced methodology it is possible to analyse quantities and variations of I/I-components. The deduced regression model can be used for the investigation of present, past and future hydrological scenarios.

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